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# Robust Gradient Estimator for Unknown Frequency Estimation in Noisy Environment: Application to Grid-Synchronization

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**ABSTRACT** Grid-connected converters are an important class of power electronic systems. Many power and energy applications require grid-connected converters. To control grid-connected converters, precise information of the grid voltage frequency and phase are required. Gradient estimators can be very useful in this regard. They are suitable to estimate the frequency and phase of the grid voltage signal. Various gradient estimators are already available in the literature e.g. regression-based techniques. However, most of them are designed by using the instantaneous estimation error as the cost-function. This amplifies the effect of noise in the estimated parameters. To overcome this issue, an integral cost-function is considered in this paper. The integral cost-function tries to minimize the estimation error over the integration window leading to reduce the effect of noise in the estimated frequency and phase. Moreover, the cost-function uses tunable forgetting factor to give more importance to recent data. The proposed gradient estimator assumes the grid frequency to be constant. However, in practice the frequency is variable with known nominal value. To overcome this problem, a frequency estimation block is coupled with the gradient estimator. The frequency estimation block uses the idea of phase-based frequency estimation. Comparative numerical simulation and experimental studies are performed to demonstrate the suitability of the proposed technique over three other advanced techniques from the literature.

**INDEX TERMS** Gradient estimator, frequency estimation, phase estimation, grid synchronization, noise robust estimation, single-phase system.

## I. INTRODUCTION

Renewable energy sources (RES) are playing a very important role in decarbonization of the existing electric power grid. The penetration of RES in the power grid is increasing at a very encouraging rate. RES are generally connected to the grid through grid-connected power converters [1]–[7]. Grid-connected converters are also used in various other power and energy systems applications, e.g. grid-connected

rectifier [8], electric vehicles (EV) on-board charger [9], islanding detection [10], active power filter [11], [12], dynamic voltage restorer [13], [14], etc. All these applications highlight the importance of designing efficient controllers of grid-connected converters.

Control of grid-connected converter is a well-studied technical problem and many results have been presented so far. Many of these results require the precise information of the grid voltage frequency and instantaneous phase. However, frequency and instantaneous phase can not be directly measured rather to be estimated from the grid voltage signal.

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of Gaussian noise. Most of the existing Kalman filters used in grid-connected converter applications assume the noise covariance to be constant. As the Hall effect sensor or the analog-to-digital converter (ADC) ages with time, the noise property of the sensor and ADC also change. This may degrade the performance of the Kalman filter in the long run. One solution is to use adaptive Kalman filter that estimate the noise online. However, this adds additional computational complexity to already computation heavy Kalman filter.

Noise is inevitable in designing the control system for grid-connected converters. The control systems are often implemented in discrete-time in micro-controller. Many low-cost micro-controllers use cheap ADC. ADC introduces noise in the measured voltage signal. Moreover, Hall effect sensors are often used to measure the grid voltage signal. Sensors also introduce noise in the measurement. As such, if proper cares are not taken, then the grid voltage signal feedback to the controller can be very noisy. This is most often the case in low-cost implementation.

To overcome the effect of noise, Kalman filter can be a suitable solution. However, as previously mentioned, adaptive Kalman filters need to be used as opposed to traditional non-adaptive Kalman filter. However, this increases the computational cost. One potential solution is to use gradient estimators that use integral cost-functions. Gradient estimators are not new in grid-synchronization application. Regression-based techniques e.g. various variants of least-squares are actually gradient estimators. These estimators are designed by considering the instantaneous estimator error as the cost-function. Then the closed-form solution of the estimator can be obtained by calculating the gradient of the instantaneous cost-function. However, in noisy environment, minimizing the instantaneous error can be problematic as this will amplify the effect of noise. To overcome this issue, integral of the estimation error cost-function is more suitable. This cost-function tries to minimize the error over the integration window leading to reduce the effect of the noise. Moreover, if a tunable forgetting factor can be included in the cost-function, this will give the designer the choice to give importance to recent data. One such cost-function has already been considered in the adaptive estimation literature [49], [50]. In this paper, a frequency adaptive gradient estimator will be developed by considering the integral of the estimation error as the cost-function to minimize the effect of the noise. The proposed gradient estimator-based synchronization technique will be very suitable for grid-synchronization application in noisy environment. Moreover, the technique presented in this paper is very general and can be applied to unknown frequency estimation of any sinusoidal signal as well.

The rest of the article is organized as follows: details of the proposed approach is given in Sec. II while the comparative experimental results and discussions are given in Sec. III. Finally, Sec. IV concludes this paper.

## II. PROPOSED APPROACH

A single-phase grid voltage signal can be written as:

$$y = A \sin(\omega t + \underbrace{\varphi}_{\Phi}) \quad (1)$$

where  $A$  is the amplitude,  $\omega = 2\pi f$  is the angular frequency (with nominal value being  $\omega_n = 100\pi$ ),  $\varphi$  is the phase angle, and  $\Phi \in [0, 2\pi)$  is the instantaneous phase of the grid voltage signal. Considering the phase angles as state variables [39], model (1) can be written as:

$$y = \underbrace{[A \sin(\varphi) \ A \cos(\varphi)]}_{\theta^T} \underbrace{\begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix}}_{\phi} \quad (2)$$

If we assume that the grid voltage is constant, then eq. (2) is a linear parametric model of the grid voltage (1), where the unknown amplitude and phase angle i.e. unknown parameter vector  $\theta$  is linearly parameterized w.r.t. the known vector  $\phi$ . In practice, the frequency  $\omega$  is also unknown with known nominal value. However, this issue will be dealt later on in this Section. Gradient estimators are generally designed by considering the estimation error as the cost-function and try to minimize the estimation error. To demonstrate this fact, let us consider the following cost-function for model (2) [49]:

$$J(\theta) = \frac{(y - \hat{y})^2}{2} = \frac{(y - \hat{\theta}^T \phi)^2}{2} \quad (3)$$

where  $\hat{\cdot}$  indicates estimated value. Gradient estimators generally involve the gradient of the cost-function (3) and has the following form:

$$\dot{\hat{\theta}} = -\Gamma \Delta J \quad (4)$$

where  $\Gamma = \Gamma^T > 0$  is the tuning parameter and the gradient  $\Delta J$  is given by:

$$\Delta J = -\phi \underbrace{(y - \hat{\theta}^T \phi)}_{\varepsilon} \quad (5)$$

Cost-function (3) considers the instantaneous error. This may be problematic in a noisy environment. To overcome this problem, considering an integral cost-function could be interesting from practical point of view. In this context, the following cost-function has been proposed in the literature [50]:

$$J(\theta) = \frac{1}{2} \iint \left\{ \phi^T(\tau) \hat{\theta}(t) - y(\tau) \right\}^2 e^{-q(t-\tau)} d\tau, \tau \leq t \quad (6)$$

where  $q > 0$  is a positive design constant that works as a forgetting factor. Cost-function (6) is also known as discount integral cost-function in the literature. An advantage of cost-function (6) is that it penalizes all past estimation error i.e. integral of the estimation error within the integration window. Moreover, the decaying exponential term in (6) gives more importance to recent data by giving less weight to earlier data. Similar to the instantaneous cost-based gradient estimator,

integral cost-based gradient estimator also takes the same form and given below:

$$\dot{\hat{\theta}} = -\Gamma \Delta J, \quad \Gamma = \Gamma^T > 0 \quad (7)$$

where the gradient of the cost-function is given below [49]:

$$\Delta J = R\hat{\theta} + Q \quad (8)$$

where  $R$  and  $Q$  are defined as:

$$R := \iint \phi(\tau)\phi(\tau)^T e^{-q(t-\tau)} d\tau,$$

$$Q := - \iint \phi(\tau)y(\tau) e^{-q(t-\tau)} d\tau.$$

where  $R \in \mathbb{R}^{2 \times 2}$  and  $Q \in \mathbb{R}^{2 \times 1}$ . By plugging in the gradient (8) in eq. (7), the integral cost-based gradient estimator can be obtained as:

$$\dot{\hat{\theta}} = -\Gamma (R\hat{\theta} + Q) \quad (9a)$$

As presented in [50], the integrals involved in the definition of  $R$  and  $Q$  can be considered as convolution integral. As such,  $R$  and  $Q$  can be generated by the following differential equations:

$$\dot{R} = -qR + \phi\phi^T \quad (9b)$$

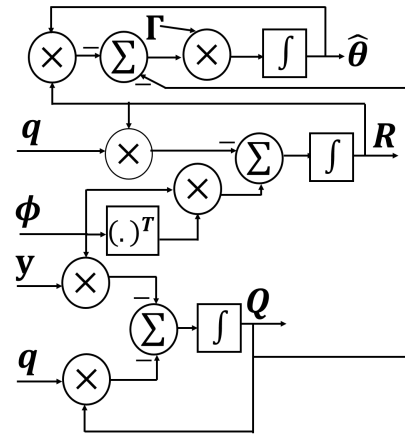
$$\dot{Q} = -qQ - y\phi \quad (9c)$$

From the estimated parameters  $\hat{\theta} = [\hat{\theta}_1; \hat{\theta}_2]$ , the phase angle can be estimated as:

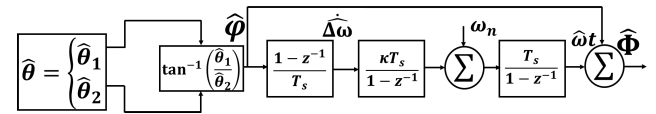
$$\hat{\phi} = \arctan \left( \frac{\hat{\theta}_1}{\hat{\theta}_2} \right) \quad (10)$$

From the estimated phase angle  $\hat{\phi}$ , using phase angle based frequency estimation technique e.g. [18], the unknown frequency can easily be estimated. To implement the proposed integral cost-based gradient estimator (GE), eq. (9) and (10) are required. The block diagram of the proposed estimator is given in Fig. 2. Details are given in Fig. 3.

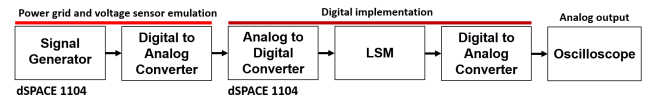
The proposed frequency adaptive gradient estimator has three parameters to tune. They are  $\Gamma$  and  $q$  in the gradient estimator block and  $\kappa$  in the frequency estimation block. The parameter  $\Gamma$  is a diagonal matrix and can be written as  $\Gamma = \gamma I_2$ ,  $\gamma > 0$ , where  $I_2$  is the identity matrix of dimension  $2 \times 2$ . The convergence speed of the proposed estimator depends on  $\gamma$  while  $q$  is the forgetting factor. The parameter  $q$  should be always selected much smaller than  $\gamma$ . Through extensive numerical simulation we found  $\gamma = 10000$  and  $q = 100$  to be good values. The parameter  $\kappa$  determines the convergence speed of the frequency estimation. This parameter has to be selected as a trade-off between fast convergence speed and acceptable transient performance. In this regard,  $\kappa = 150$  was found to be a good value.



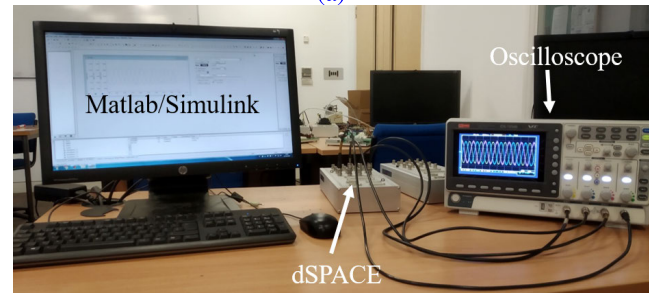
**FIGURE 2.** Block diagram of the proposed estimator. This estimator requires the value of the estimated frequency, which is obtained from Fig. 3.



**FIGURE 3.** Phase angle-based frequency estimation technique using the proposed gradient estimator. Input of the frequency estimation block are obtained from Fig. 2.



(a)



(b)

**FIGURE 4.** Experimental setup, (a): overview, (b): actual setup.

### III. RESULTS AND DISCUSSIONS

In this section, comparative simulation and experimental studies are considered. Numerical simulation studies are performed in Matlab/Simulink. As experimental platform, the dSPACE 1104 board has been considered. The experimental setup considered in this work is similar to [46, Fig. 12]. Overview of the experimental setup is given in Fig. 4. As mentioned in the Introduction Section, Kalman filter is well known technique in grid synchronization literature. Kalman filter performs well in noisy environment. As such we have selected the linear Kalman filter frequency-locked loop (LKF-FLL) [51] as one of the comparison technique.



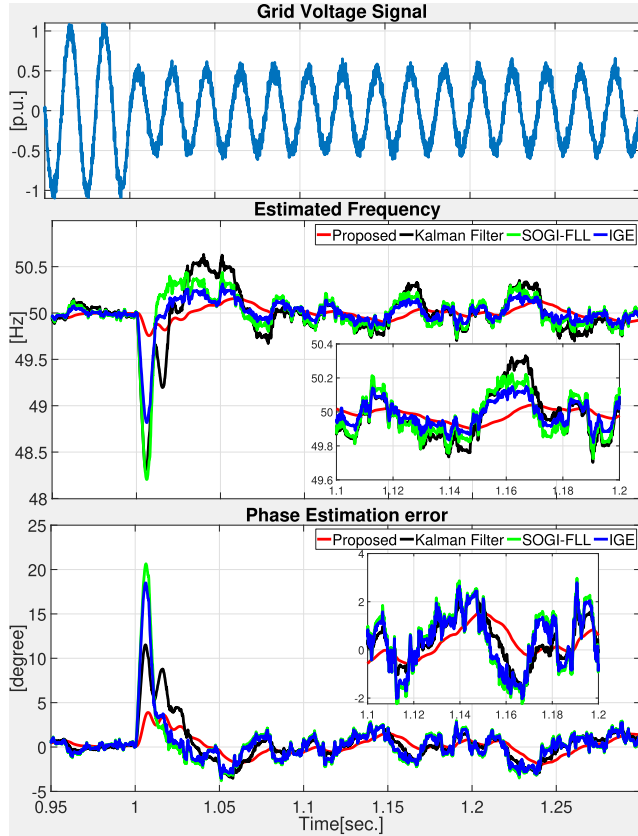


FIGURE 5. Simulation test results for  $-0.5p.u.$  amplitude step change.

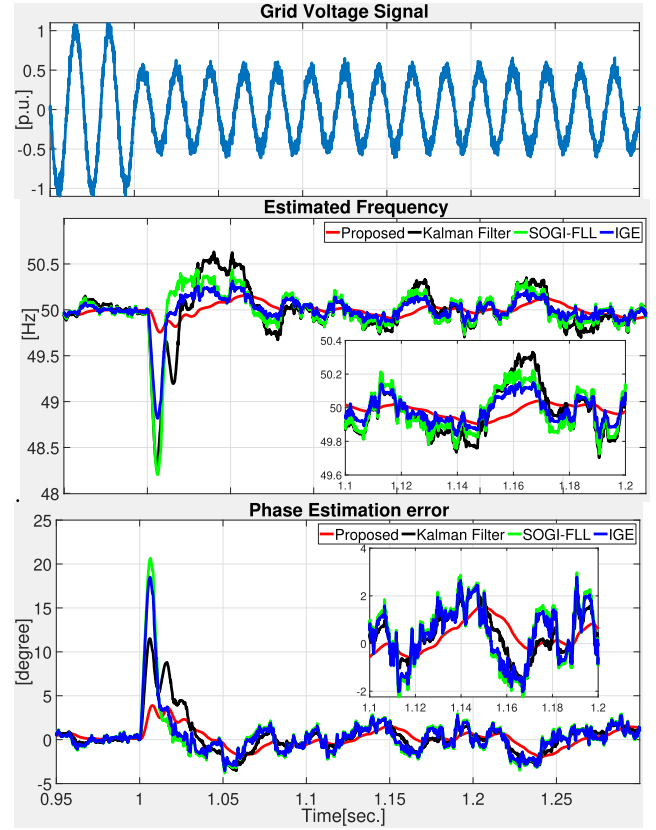


FIGURE 6. Experimental test results for  $-0.5p.u.$  amplitude step change.

In addition, instantaneous cost-function-based gradient estimator (IGE) [18] and second-order generalized integrator FLL (SOGI-FLL) [36] are also considered as the comparative techniques. The parameters of the proposed technique have been selected as:  $\gamma = 10^6$ ,  $q = 100$ , and  $\kappa = 150$ . The parameters of LKF-FLL are selected as:  $P_0 = 1000I_2$ ,  $Q = 0.02I_2$ ,  $R = 1$ ,  $x_0 = [0.01; 0.01]$ , and  $\gamma = 40\omega_n$ . Parameters of IGE have been selected as:  $\alpha = 400$  and  $k = 50$ . Parameters of SOGI-FLL are selected as:  $k = \sqrt{2}$  and  $\gamma = 50$ . All the continuous integrator are discretized using trapezoidal method with a sampling period  $T_s = 10^{-4}sec$ . To emulate noisy environment, Gaussian noise has been added to the voltage signal. The considered noisy signal has signal-to-noise ratio (SNR) of 27dB.

#### 1) TEST-I: $-0.5P.U.$ AMPLITUDE STEP CHANGE

In this test, the grid voltage was initially set as 1p.u. Suddenly the voltage dropped to 0.5p.u. Many grid codes require the grid-connected converters to be connected to the grid despite this kind of low-voltage condition. The numerical simulation and experimental results for Test-I are given in Figs. 5 and 6. Results show that all techniques are very quick to respond to large change in the amplitude. SOGI-FLL and LKF-FLL have very high peak overshoot of  $\approx 2Hz$ . Gradient estimators have significantly smaller overshoot w.r.t. FLL techniques. FLL techniques demonstrated high peak overshoot for phase

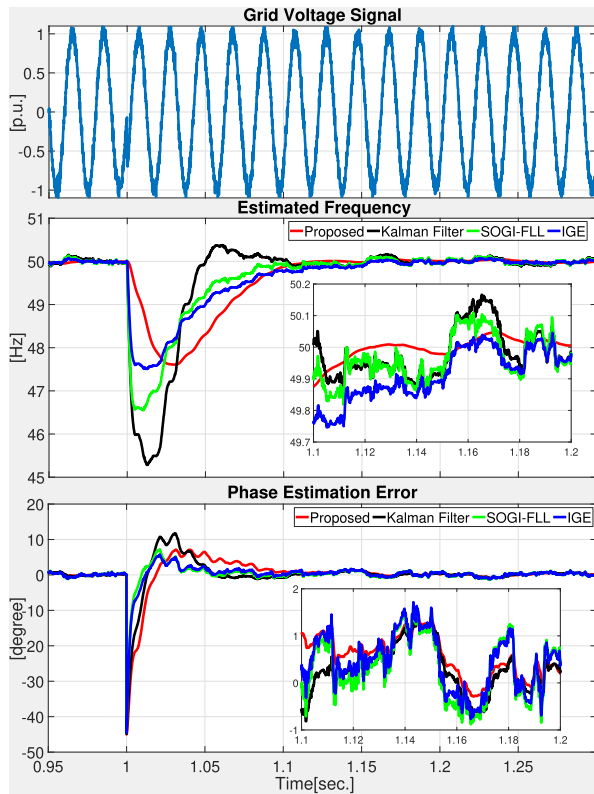
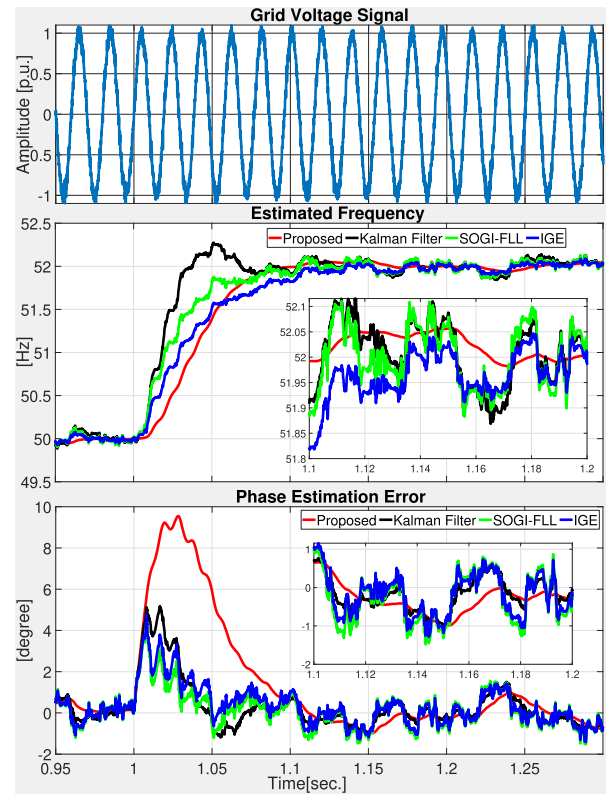
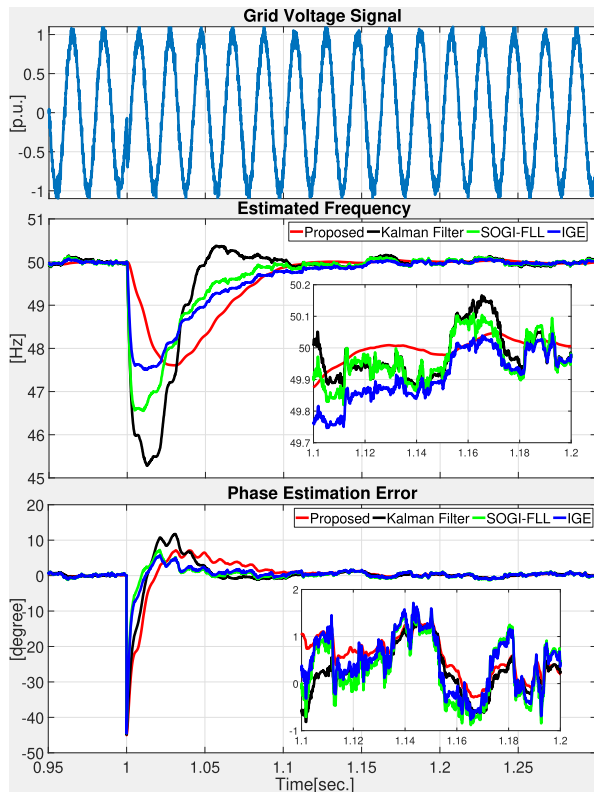
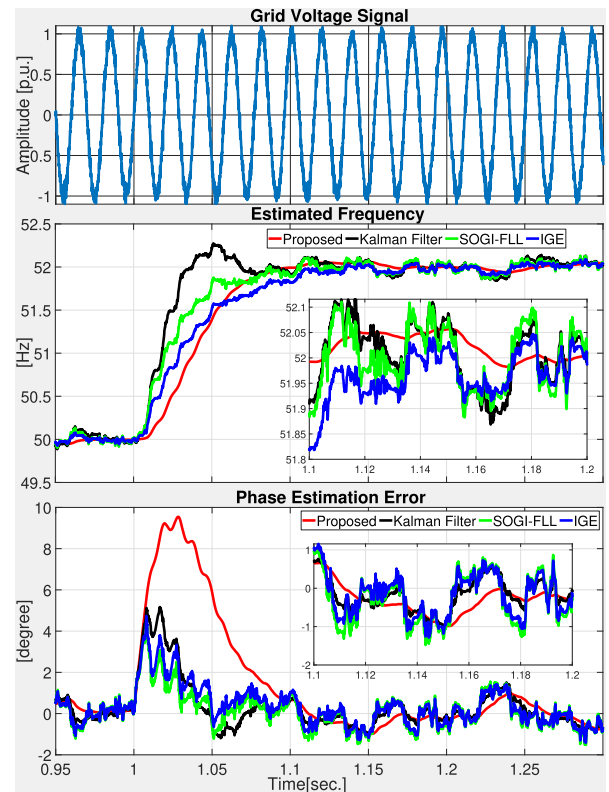
estimation error also. The proposed technique has a peak overshoot of only  $\approx 4^\circ$  while it is 5 times more for SOGI-FLL at  $\approx 20^\circ$ . These results demonstrate the suitability of the proposed technique when large voltage sag occurs in the grid voltage signal.

#### 2) TEST-II: $-45^\circ$ PHASE STEP CHANGE

In this test, the phase angle suddenly changed from  $0^\circ$  to  $-45^\circ$ . This type of test condition is very challenging for any grid-synchronization algorithm. The numerical simulation and experimental results for Test-II are given in Figs. 7 and 8. Experimental results show that all techniques have similar convergence speed. However, the proposed technique has significantly smaller peak overshoot w.r.t. FLL-based techniques. The peak frequency overshoot of the gradient estimators are similar. However, zoomed figure shows that the proposed technique is less sensitive to noise than IGE. Similar performance can be observed for the phase estimation error as well. These demonstrate the suitability of the proposed technique when sudden large jump in phase angle occurs in the grid voltage signal.

#### 3) TEST-III: $+2Hz$ FREQUENCY STEP CHANGE

In this test, the frequency suddenly changed from 50Hz to 52Hz. The numerical simulation and experimental results for Test-III are given in Figs. 9 and 10. Experimental results

FIGURE 7. Simulation test results for  $-45^\circ$  phase step change.FIGURE 9. Simulation test results for  $+2\text{Hz}$  frequency step change.FIGURE 8. Experimental test results for  $-45^\circ$  phase step change.FIGURE 10. Experimental test results for  $+2\text{Hz}$  frequency step change.

demonstrate that the convergence times all techniques are similar. Except LKF-FLL, the estimated frequency by the

other techniques did not show any peak overshoot. Zoomed figure shows that the proposed technique is less sensitive to

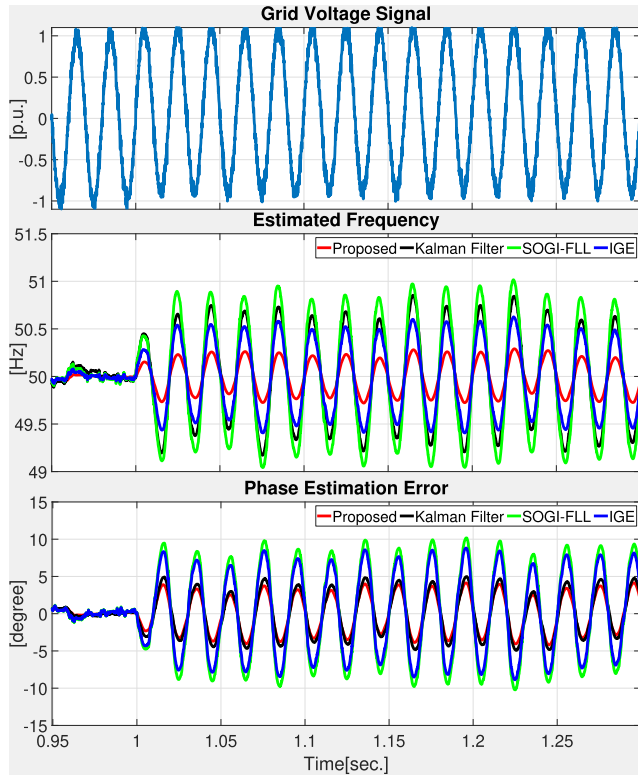


FIGURE 11. Simulation test results for +0.1p.u. DC step change.

noise than the other techniques. In term of phase estimation, the proposed technique has the slowest convergence time. However, the proposed technique showed least sensitivity to noise.

#### 4) TEST-IV: +0.1P.U. DC STEP CHANGE

In this paper, we did not consider the effect of DC offset in model development. However, due to signal conversion or transformer saturation issue, sometimes DC offset is unavoidable. This test consider the effect of DC offset in the estimated parameters. In this test, a DC offset +0.1p.u. is suddenly added to the grid voltage signal. In the presence of DC offset, estimation ripples are present in the estimated frequency and phase by all techniques. However, the proposed technique has the lowest ripple magnitude. The ripple magnitudes are  $\approx 2$  times smaller than SOGI-FLL. These results demonstrate the suitability of the proposed technique in the presence of DC offset.

#### 5) TEST-V: DISTORTED GRID VOLTAGE

In today's power system, the effect of harmonics cannot be longer neglected. The rise of nonlinear loads and switch mode power supplies are making the grid more and more distorted. To test the effectiveness of the proposed technique, a distorted grid voltage is considered. In this test, the grid voltage is suddenly corrupted with 6.75% total harmonic distortions (THD). The considered harmonics are: 20Hz

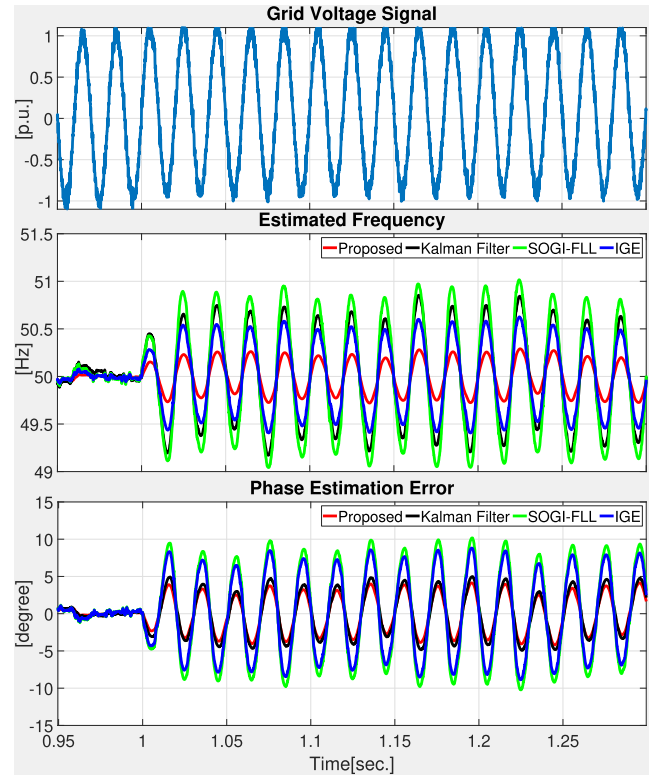


FIGURE 12. Experimental test results for +0.1p.u. DC step change.

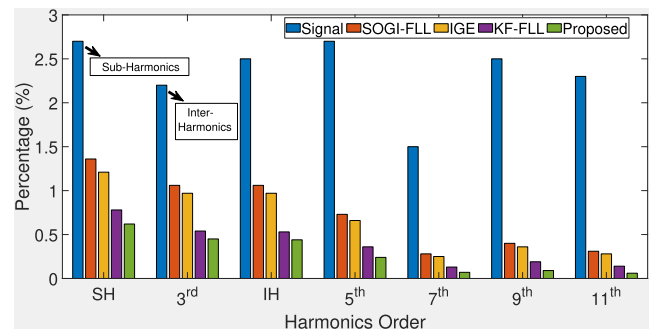


FIGURE 13. Summary of the harmonics robustness test.

sub-harmonics - 2.7%, 3<sup>rd</sup> - 2.2%, 160Hz inter-harmonics - 2.5%, 5<sup>th</sup> - 2.7%, 7<sup>th</sup> - 1.5%, 9<sup>th</sup> - 2.5%, and 11<sup>th</sup> - 2.3%. A summary of the harmonics generated by the comparative techniques are given in Fig. 13. Figure 13 shows that the proposed technique has the lowest total harmonic distortion (THD). The numerical simulation results for Test-V are given in Fig. 14. Despite the grid voltage being highly distorted, the proposed technique's frequency estimation ripple is bounded by mere  $\pm 0.1$ Hz while it is at least 4 times higher for LKF-FLL. However, the performance of LKF-FLL improved in phase estimation error case as the peak-to-peak estimation error ripple of LKF-FLL is comparable to the proposed technique. Simulation results demonstrated the suitability of the proposed technique in heavily distorted grid.



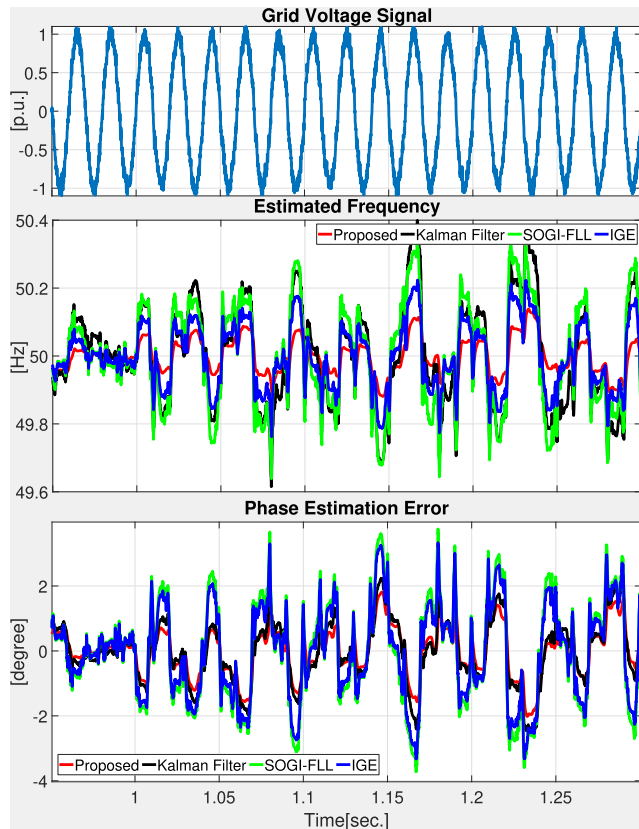


FIGURE 14. Simulation test results for the harmonics test case.

#### IV. CONCLUSION AND FUTURE WORKS

This paper developed an integral cost-function-based gradient estimator for frequency and phase estimation of single-phase grid voltage signal. First, a linear parametric model of the grid voltage is considered. The model assumed the grid frequency to be known while amplitude and phase angle to be unknown. Then using existing results from the adaptive estimation literature, an integral of the estimation error cost-function is considered. Unlike instantaneous error cost-function, this cost-function penalizes the estimation error over the integration window. This helps to reduce the effect of noise. Based on the integral cost-function, a gradient estimator is designed to estimate the unknown frequency and phase of the grid voltage signal. To make the gradient estimator frequency-adaptive, a frequency estimation law is proposed. Extensive comparative numerical simulation and experimental studies are considered using various challenging test scenarios. Comparative results with linear Kalman filter frequency-locked loop (LKF-FLL) demonstrated the suitability of the proposed technique. Control parameters of the proposed integral of estimation error cost-function-based gradient estimator are chosen using trial and error method. However, this is not systematic. Small-signal modeling-based parameter tuning will be considered in a future work. The proposed technique require the calculation of integrals. This comparatively slows down the dynamic response with respect to some other techniques available in the literature. As such

the application of this technique can be limiting where very fast dynamic response is required. Dynamic performance improvement will also be considered as a future work.

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